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Initiation of Disjunctive Smooth Pursuit in Monkeys: Evidence that Hering's Law of Equal Innervation is not Obeyed by the Smooth Pursuit System

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Monkeys generated disjunctive smooth pursuit eye movements when they tracked visual targets that moved toward or away from them. Eye acceleration was computed during the initial 100 msec of pursuit (the open-loop interval) for various target trajectories. The initial acceleration of either eye was a function of the target's motion with respect to that eye, regardless of whether or not the pursuit was conjugate or disjunctive, or performed with one eye occluded. Eye movements produced by fusional vergence could be separated temporally from eye movements produced by smooth pursuit using step-ramp paradigms. The separation of the two responses demonstrates that the fusional vergence system operates in parallel with the smooth pursuit system, presumably to minimize disparity, but not to generate disjunctive components of smooth pursuit eye movements.

Eye movements Vergence Smooth pursuit Monkey

INTRODUCTION

There are the two basic patterns of binocular eye movements: (i) conjugate movements during which the eyes are yoked and move in the same direction through the same angle; (ii) disjunctive eye movements during which the eyes are not yoked and move in opposite directions and/or rotate through different angles. Hering (1868) argued that the eyes cannot be moved independently, but rather, "the musculature of both eyes reacts simultaneously to one and the same impulse of will". To account for disjunctive eye movements, Hering argued that the seemingly independent movements of the eyes were produced by linear addition of "two different innervations" corresponding to separate conjugate and symmetric vergence commands. If these commands were applied simultaneously to both eyes, they would be additive in one eye and subtractive in the other thereby producing disjunctive eye movements. Nearly a century later, Hering's idea was supported by Yarbus's (1967) classic observations of binocular eye movements. In accord with this viewpoint, saccadic, smooth pursuit, and vestibular eye movements [vestibulo-ocular reflex (VOR)] are usually classified as conjugate and are thought to be produced by oculomotor sub-systems that respond to conjugate retinal errors. In contrast, vergence eye movements are thought to be produced by a separate sub-system that responds to binocular disparity, accommodation errors, or binocular distance cues (Dodge, 1903; Erkelens, Steinman & Collewijn, 1989; Leigh & Zee, 1991).

Several recent studies suggest, however, that Hering's concept is over-simplified. When humans (Enright, 1984; Erkelens *et al.*, 1989; Kenyon, Ciuffreda & Stark, 1980; Ono & Nakamizo, 1978; Zee, Fitzgibbon & Optican, 1992) and monkeys (Maxwell & King, 1992) make saccades between targets placed at different distances from the subject, the saccades are disjunctive. Qualitatively, the saccadic trajectories are similar to those described by Yarbus (1967), with slow changes in vergence at the beginning and end, and rapid changes in vergence during the saccade itself. However, the rapid vergence change cannot be accounted for by the linear addition of classically described fusional vergence and a conjugate saccade as suggested by Hering and Yarbus (Erkelens *et al.*, 1989; Kenyon *et al.*, 1980; Maxwell & King, 1992; Ono & Nakamizo, 1978) since fusional vergence has a much slower time-course than that of saccades. These studies imply either that the vergence

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sub-system is capable of producing rapid saccade-like vergence changes (Mays & Gamlin, 1992; Zee *et al.*, 1992) in conjunction with conjugate saccades, or that the saccadic system itself can generate innervations for each eye's musculature in response to that eye's retinal error.

In other experiments, Snyder and King (1992) and Paige and Tomko (1991) have shown that the VOR is disjunctive under appropriate kinematic conditions. For example, if a subject fixates a target directly ahead and moves linearly toward or away from the target, the linear VOR generates symmetric vergence movements (Paige & Tomko, 1991). The dynamics of the vestibular induced eye movements are consistent with the VOR, and they occur in darkness (Snyder & King, 1992) or in response to high frequency linear oscillations [*ca* 5 Hz (Paige, 1991)], suggesting that disjunctive VORs are driven directly by the vestibular system and not by a combination of conjugate VORs and symmetric vergence movements produced by a vergence sub-system.

These studies suggest the possibility that disjunctive eye movements may result from neural commands produced by the saccadic and vestibular systems for each eye in response to appropriate visual or kinematic stimuli. Thus these systems are probably not organized as intrinsically "conjugate" eye movement systems. Furthermore, single unit studies (McConville, Tomlinson, King, Paige & Na, 1994) show that premotor cells in the vestibular nuclei encode left-or right-eye position, but not conjugate eye position (the average of left-and right-eye position). These physiological data also suggest that *premotor* eye movement commands may be encoded separately for each eye.

Saccades are driven by error signals derived from internal representations of a desired target's position rather than by instantaneous visual feedback, and can be voluntarily produced in the dark without visual stimulation. Thus, although monocular retinal errors may be used to create disjunctive saccades, it is also likely that non-retinal cues, binocular in nature, are used to create conjugate saccades. Although there is evidence that the VOR directly produces disjunctive eye movements (Paige & Tomko, 1991; Snyder & King, 1992; Viirre, Cadera & Vilis, 1988), the pathways and mechanisms remain unclear. In contrast to saccades and the VOR, smooth pursuit eye movements are directly driven by visual signals that encode the retinal position and motion of the selected target, and smooth pursuit eye movements normally cannot be produced in the absence of a visual stimulus. Pursuit movements are usually regarded as conjugate, but the experimental results presented in this paper show that they can be disjunctive if the target's distance from the subject changes [for an early demonstration of this, see Yarbus (1967)]. To refute Hering's hypothesis, however, additional evidence must be obtained that explicitly distinguishes disjunctive smooth pursuit from fusional vergence. To obtain such evidence, we examined the initiation of smooth pursuit in experimental paradigms that isolated disparity-driven vergence from retinal-slip-driven smooth pursuit.

MATERIALS AND METHODS

Surgical preparation

Two male monkeys (*Macaca mulatta*) were fitted with head stabilization platforms attached to the skull with stainless steel bone screws and dental acrylic. Eye coils were implanted in each eye for chronic recording of binocular eye movements (Robinson, 1963). The eye coils, consisting of three loops of Teflon-insulated multi-strand wire, were surgically implanted under the conjunctiva using the method of Judge, Richmond and Chu (1980). Surgeries were performed under aseptic conditions using gas anesthesia (Isoflourane). Post-operative analgesics were provided as indicated. Animal care and surgical procedures were in full accordance with the *Guiding principles for research involving animals and human beings* approved by the Council of the American Physiological Society.

Experimental apparatus/training

During experiments, the monkey was seated in a primate chair. The chair was locked in place on a stationary table and positioned directly in front of a vertical tangent screen at a distance of 2 m. A second screen (near screen), oriented in a horizontal plane, was attached to the eye coil frame and positioned directly in front of the monkey at about nose level. The subject's head and the field coils (CNC Engineering) were stabilized relative to the table, so that the eye coil signals were proportional to the position of the eyes in the orbits.

Before collecting data for these experiments, each monkey was trained to visually fixate and track small targets projected on either the far or near screen for juice rewards. The position and speed of the target were computer controlled using mirror galvanometers (General Scanning).

Experimental design/paradigms

During recording sessions, the monkey viewed the laser target in a dimly illuminated room. The monkey was rewarded with a drop of apple juice for accurately fixating the target with both eyes for a variable time interval (typically 1500 msec). The accuracy criterion was usually 1 deg for each eye, but was occasionally adjusted to be larger (up to 4 deg) or smaller (0.8 deg) during a trial depending on the difficulty of the task. Eye position was calibrated at the beginning of each recording session by requiring the monkey to fixate an array of target positions on both the far and near screens. From these fixation data, the computer constructed interpolation tables from which either eye's position could be accurately determined in real time for any target location on either display screen. These data also enabled the computer to determine the target's retinal position on each eye so that the target's motion could be controlled with respect to eye position (see below). Several times during the course of these experiments, each eye was calibrated while the other was occluded. This procedure enabled us to assess if there were any strabismus present that may have been caused by the eye coil surgery. There was none in either monkey.

The experimental paradigm was relatively straightforward. Smooth pursuit eye movements were studied while the monkey tracked targets that moved with step-ramp trajectories (Rashbass, 1961). The monkey initiated trials by fixating the laser spot at a randomly varied initial position. After a random time delay, the target abruptly stepped to a new position, and then moved smoothly, in the opposite direction, at a constant speed (Lisberger & Westbrook, 1985). The size of the step was small (1–2 deg) and was adjusted in amplitude to delay the occurrence of catch-up saccades. The direction of the step and the speed of the smoothly moving target were randomly varied.

The laser was projected on the far screen to elicit conjugate pursuit. Target motion was always to the left or right, evoking horizontal pursuit at speeds ranging from 5 to 30 deg/sec. The laser was projected on the near screen to elicit disjunctive pursuit.* Target trajectories on the near screen were oriented parallel to the animal's sagittal plane, and target motion was either toward or away from the monkey in order to elicit convergent or divergent pursuit respectively. At the end of the step-ramp, the target always remained on the screen for a fixation interval prior to the end of the trial. The near screen had a slight vertical tilt, so there was always a small conjugate component of vertical pursuit associated with the disjunctive horizontal pursuit components.

Initial and final target positions ranged from about 8 to 20 cm from the monkey's eyes on the near screen eliciting vergences from about 2 to 18 deg. The surface of the near screen was covered with a sheet of opaque, white drafting paper and was not highly reflective, so the target spot appeared dim and somewhat blurred regardless of its position on the screen. Thus it provided a poor stimulus for accommodation.

Three paradigms were employed to investigate vergence pursuit: disjunctive pursuit of a binocularly viewed near target, disjunctive pursuit of a monocularly viewed near target, and conjugate pursuit of a binocularly viewed far target. For monocularly viewed targets, the left eye was occluded with an opaque eye patch.

During a typical trial, the monkey usually responded to the visual stimulus by initiating smooth pursuit eye movements in the direction of target motion and then making a "catch-up" saccade to place the target on the fovea. Eye movements were analyzed with emphasis on the initial interval of pursuit (< 100 msec) which occurs before the target is acquired by the fovea, and before visual feedback can be used by the oculomotor system as an error signal to correct tracking performance. Lisberger and Westbrook (1985) have called this initial pursuit response the "open-loop" interval because the oculomotor system responds to the initial visual error, and its response during the open-loop interval is not modified by eye-movement-induced visual feedback. Trials were aborted if the subject failed to acquire the laser target within 800 msec and track it within the eye position error windows for the remainder of the trial. These criteria forced the monkey to work diligently, but still allowed sufficient time for the animal to correctly complete most of the trials.

Each combination of stimulus condition (i.e. target speed, initial position, and direction) was run approx. 50 times during each experimental session. Different trials were randomly interleaved to minimize prediction of target motion.

*Because of the geometry of vergence pursuit, a constant rotational speed of the mirror galvanometers would produce a non-linear retinal image speed related to the distance of the target from the monkey's eyes. Since we were interested in analyzing the first 100 msec of pursuit (the open-loop interval), the mirror's rotation was controlled by the computer to produce constant velocity retinal image motion during a time period that included the open-loop interval.

Data acquisition

The analog target position signals from the galvanometers and the eye position signals from the scleral search coils were low-pass filtered (−3 dB at 80 Hz). These data were then digitized with 12-bit resolution and stored on a hard disk at the end of each trial. Data were acquired and behavior was operantly controlled using custom software developed for an IBM compatible PC operating under Microsoft Windows.

Data analysis

Raw data were analyzed on a Sun workstation. Eye position data were differentiated to obtain eye velocity using a two-point central difference filter with a step size of 8 msec (Bahill & McDonald, 1983). Eye acceleration during the open-loop interval was computed from eye velocity records by averaging over 20 msec intervals (see below). Data were analyzed on a trial-by-trial basis. If the monkey made a saccade within 100 msec of the target's appearance (i.e. premature saccade) or failed to be within 4 deg of the target at the end of a trial, the trial was discarded. The remaining trials were then analyzed individually for pursuit speed and acceleration in bins aligned on pursuit onset. Pursuit onset for each trial was chosen graphically by displaying the data for the experimenter to manually select the time when pursuit velocity first diverged from zero. The onset of pursuit was usually determined from the right horizontal eye velocity records, although for some experiments, latencies were determined from left-eye horizontal or right-eye vertical records. Trials were then aligned and averaged according to stimulus conditions (e.g. direction of pursuit, target speed) and displayed or plotted for further examination. In addition, tables of ASCII data were created by the computer. Values of latency, eye speed, and acceleration were grouped in tables according to stimulus condition. These data were transferred to an IBM compatible PC for final analysis and statistical evaluation using the commercial programs, SYSTAT and SigmaPlot.

RESULTS

The experiments were designed to quantitatively compare the initiation of disjunctive and conjugate pursuit responses made during binocular or monocular

viewing conditions. Monkeys generated disjunctive pursuit when they tracked targets that moved in their mid-saggital plane (symmetric vergence) or in a saggital plane aligned with or eccentric to their left eye (asymmetric vergence).

Figure 1 shows 10 superimposed trials during which the target moved at 16 deg/sec toward the animal in a sagittal plane aligned with the left eye. In this figure, individual trials were aligned on pursuit onset (see Materials and Methods). During this paradigm, the target's image was stationary near the fovea of the left eye, but moved leftward away from the fovea of the right eye. Consistent with this pattern of retinal slip, the left eye was stationary (upper traces) and the right eye pursued the target by rotating to the left (middle traces). Both eyes moved conjugately downward (lowermost traces, right eye shown) since the target was displayed on a slightly inclined screen. The initial 100 msec of pursuit, delimited by the two dotted, vertical lines, is the open-loop interval. Figure 2 shows averaged eye speed (aligned on pursuit onset, see Materials and Methods) before, during, and after the open-loop interval for 46 trials from the same experiment (including the 10 trials illustrated in Fig. 1). Notice that left-eye speed was zero during the open-loop interval (upper traces), consistent with the retinal slip of the target's image on the left eye, but that right-eye speed (middle traces) increased smoothly over the same interval, consistent with the retinal slip of the target's image on the right eye. Each set of traces is comprised of the mean eye speed (bold line) ± 1 SE (thin lines, about 46 trials). The latency of smooth pursuit movements (averaged across all initial target positions and speeds) was 165 ± 5 msec for convergent pursuit and 141 ± 3 msec for divergent pursuit in one monkey, and 267 ± 6 msec for convergent pursuit and 225 ± 6 msec for divergent pursuit in the other monkey. Although the pursuit latency of the second monkey was somewhat longer than that of the first monkey, it is not excessive given the small, dim target and retinal eccentricities that we used (Lisberger & Westbrook, 1985).

Figure 3 shows the relationship between eye speed during the open-loop interval and target speed for one monkey. In order to analyze these data, the open-loop interval was divided into three 20 msec time periods: an early interval (15–35 msec after the onset of pursuit), an intermediate interval (45–65 msec), and a late interval (75–95 msec). Average eye speed was computed during these intervals and then plotted as a function of target speed relative to that eye. For the trials shown in Fig. 3, the target was aligned with the left eye, so left-eye speed was zero during the open-loop interval (Fig. 2). Thus, only right-eye speed is plotted in Fig. 3. Right-eye speed was negative for pursuit toward the animal (labeled "convergence") and positive for pursuit away from the animal (labeled "divergence"). In either direction, the eye speed responses formed three characteristic sets according to which interval was plotted. During the early interval (within 35 msec of the onset of pursuit), right-eye speed was small (<3 deg/sec) and relatively independent of target speed (●). During the two later intervals, right-eye

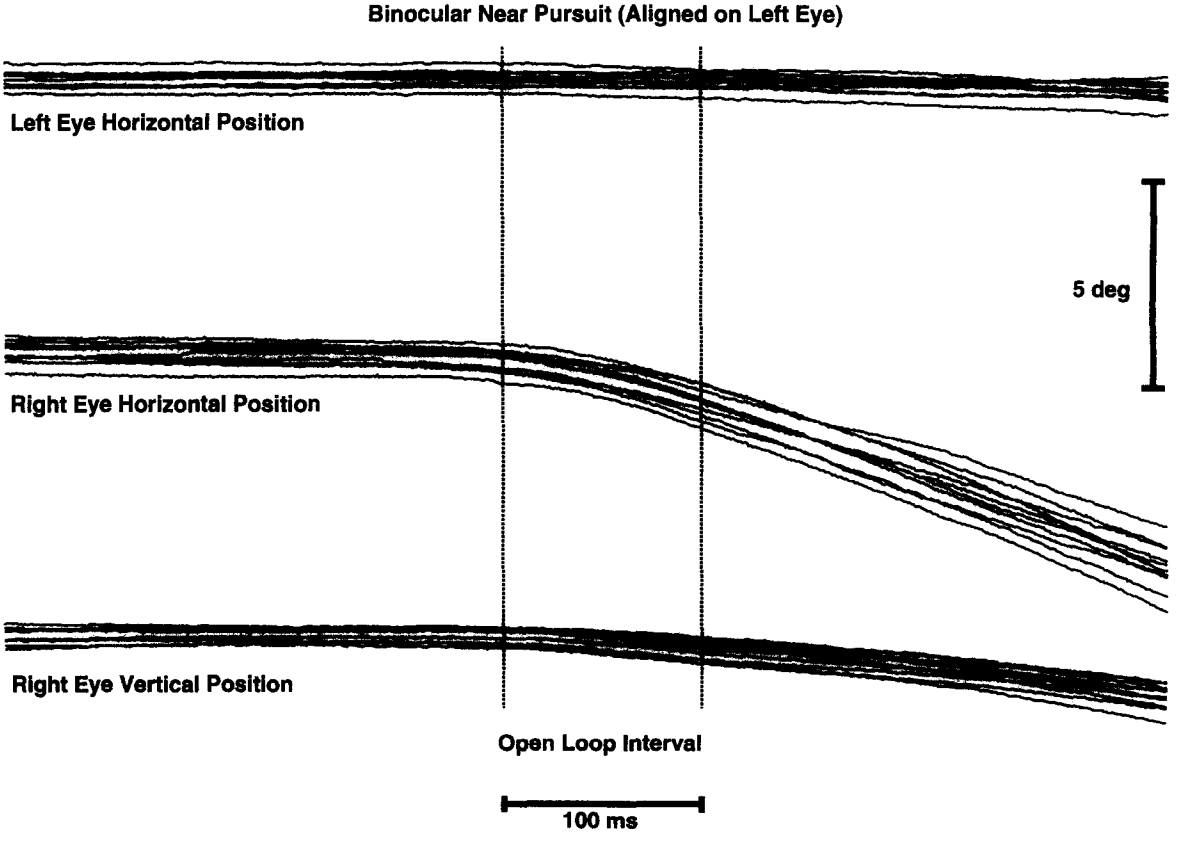

FIGURE 1. Eye position records during the initiation of disjunctive smooth pursuit of a target aligned with the left eye. Target speed was 16 deg/sec. Individual records from 10 trials are superimposed.

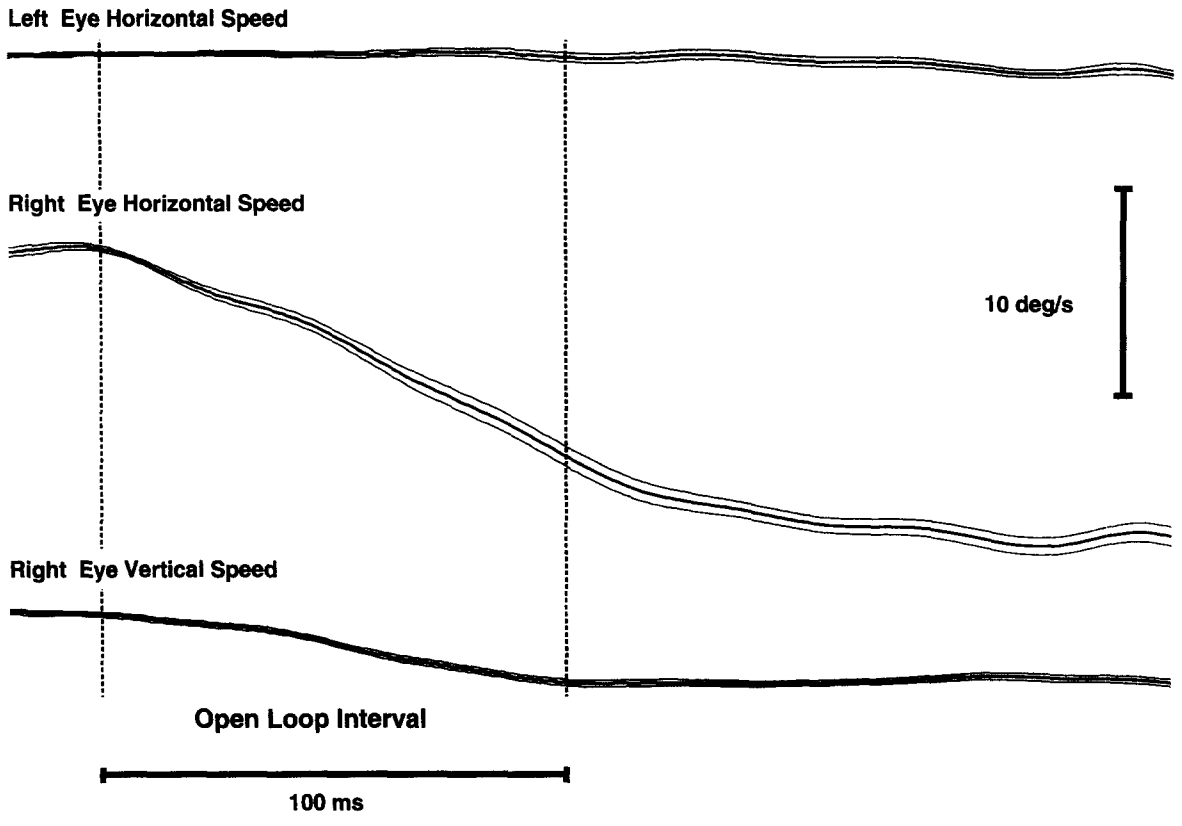

FIGURE 2. Eye speed during the initiation of disjunctive smooth pursuit of a target aligned with the left eye. Averaged eye speed is shown as a bold line bracketed by a pair of thiner lines representing ±1 SE about the mean (46 trials). See text for details.

speed was a function of target speed, and was greatest near the end of the open-loop interval (75–95 msec, ▲).

Eye acceleration is also related to target speed during the open-loop interval. Figure 4 shows this relationship for the experiment illustrated in Fig. 3. The acceleration data form a single characteristic, although there is a weak tendency for eye acceleration to decrease during the later intervals. Peak eye accelerations of 100 deg/sec^2 were achieved for target speeds of 20 deg/sec. Eye acceleration appeared to saturate for retinal target speeds in excess of 20 deg/sec, as can be seen by the divergence trials.

These results were not dependent on the target's alignment with one eye. Similar findings were obtained for two other target trajectories: (i) symmetric pursuit of a target positioned along the mid-sagittal plane; (ii) asymmetric pursuit of a the target displaced eccentrically to both eyes [so that the ipsilateral eye (with respect to the target) pursued the target over a smaller angle than the contralateral eye]. Right-eye speed and acceleration are compared for all three target trajectories (aligned, solid symbols; mid-sagittal, open symbols; eccentric left, dotted open symbols) in Figs 5 and 6 respectively. Figure 6 shows that for every condition a single linear characteristic related the acceleration of the right eye to target speed with respect to the right eye during the open-loop interval.

The data presented in Figs 1–6 are from trials during which the target moved differentially across the retinas of the two eyes, and might therefore, contain interactions between smooth pursuit (driven by retinal slip) and fusional vergence subsystems (driven by binocular disparity or other binocular cues). To examine possible interactions between pursuit and vergence, we compared conjugate pursuit of a far target with disjunctive pursuit of a near target for similar target speeds and retinal errors. Figure 7 shows the averaged speed of the right eye (all traces aligned on pursuit onset), when the monkey tracked a target aligned with the left eye (disjunctive "near pursuit", upper trace) and the averaged speed of the right eye when the monkey tracked a far target (conjugate "far pursuit", lower traces). If the disjunctive pursuit were produced by summing motor commands from separate conjugate and vergence sub-systems, we might expect to detect a difference between the trajectories for near and far pursuit, since the time–course of the fusional vergence system is sluggish and the response is driven by retinal disparity rather than retinal slip (Rashbass & Westheimer, 1961a,b). Figure 7 shows, however, that there was no discernible difference between the two trajectories. Figure 8 quantitatively compares open-loop acceleration during disjunctive (solid symbols) and conjugate (open symbols) smooth pursuit. A single characteristic suffices to account for all of the data, demonstrating that there was no quantitative difference between disjunctive and conjugate pursuit during the open-loop interval.

Because we employed step-ramp target motions, the initial disparity of the target was always opposite in direction from the pursuit response. For example, during the convergence pursuit trials shown in Figs 1 and 2, the target stepped 1–2 deg *away* from the animal before moving smoothly *toward* the animal. For these trials, the animal was presented with an initial *uncrossed* disparity

error that should have initiated a *divergent* eye movement opposite in direction from the pursuit response. We could not detect these responses in our data (see Figs 1 and 2), perhaps because the initial disparity, and the response to it, was quite small. Evidence to support this conclusion was obtained from additional control experiments. Figure 9 shows eye position records from 10 near pursuit trials (aligned at trial onset) arranged so that the target approached the monkey in the animal's mid-sagittal plane (symmetric pursuit). For these trials, the amplitude of the step was made intentionally large in order to produce an initial 10 deg uncrossed disparity stimulus. With the larger step, there was an obvious divergence response that occurred with a shorter latency (148 ± 4 msec, determined from eye *speed* records) than the disjunctive pursuit response (397 ± 6 msec). The first vertical, dashed line shows the onset of the symmetric, disparity driven vergence eye movement. Since the horizontal eye movements were determined by superimposed vergence and pursuit responses, the onset of the smooth pursuit component could not be determined from the horizontal eye movement records. Instead, it was determined from the vertical eye *speed* records (not shown), and is indicated by the second dashed line. This method works because the vertical eye movements were driven by conjugate retinal slip, not by horizontal disparity. Shortly after the onset of the pursuit response (as determined from the vertical records), the movements of the horizontal eye position traces reverse to the convergent direction presumably because the eye speed

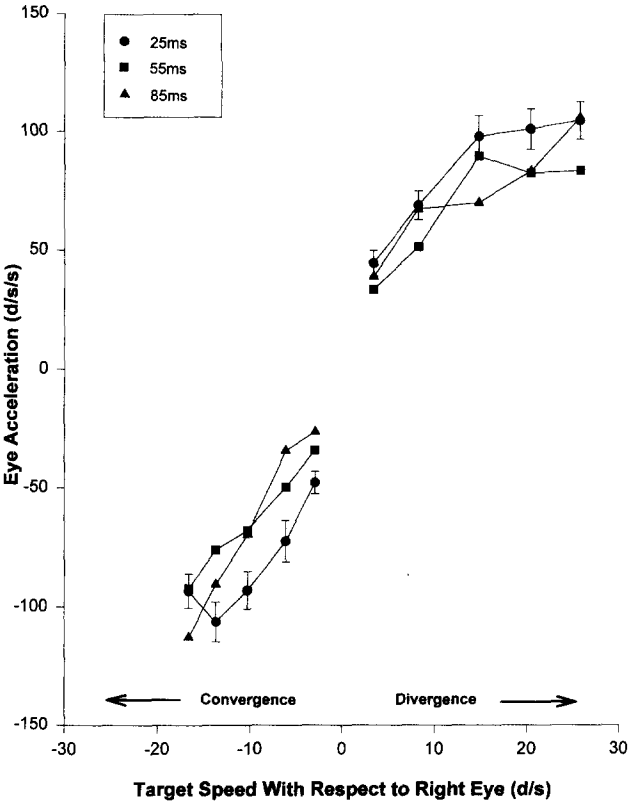

FIGURE 4. Right-eye acceleration plotted as a function of target speed with respect to the right eye (retinal slip) during the open-loop interval. Vertical bars indicate ±1 SE during the initial part of the open-loop interval (15–35 msec, ●). SEs were similar in magnitude for the remainder of the open-loop interval, but are not shown for clarity. The times in the legend box denote the middle of the 20 msec intervals over which average acceleration was computed (e.g. 15–25, 45–65, and 75–95 msec).

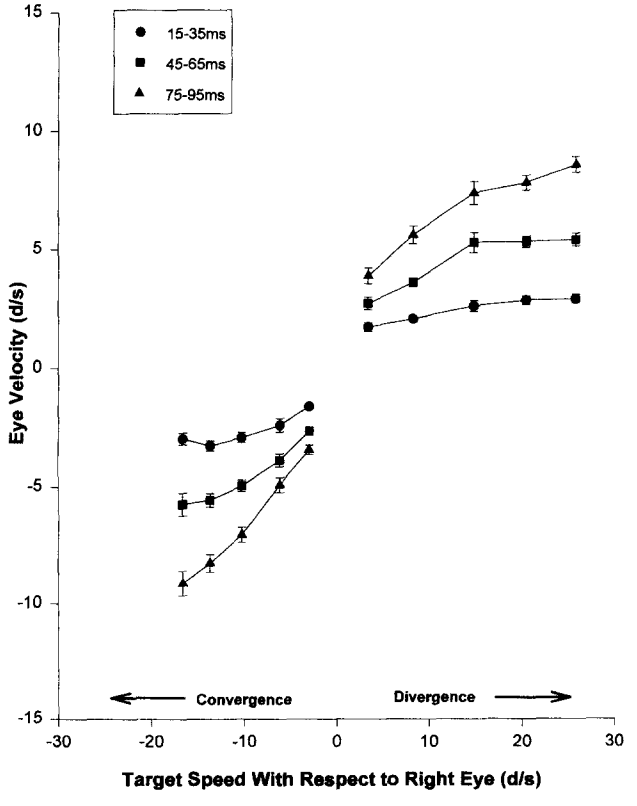

FIGURE 3. Right-eye speed plotted as a function of target speed with respect to the right eye (retinal slip). Data are shown for three time intervals during the open-loop interval. Vertical bars represent ±1 SE.

generated by the pursuit component exceeded eye speed generated by the vergence component. The latency of the smooth pursuit component (397 msec) was longer than the latency of this animal's responses to similar target speeds when the step was small (224 msec). Although the latency difference might be related to an interaction between pursuit and vergence, it may also be related to the peripheral displacement (5 deg) of the target on the animal's retinas. Peripheral targets are detected with longer latencies and initially tracked with smaller accelerations (Lisberger & Westbrook, 1985). Regardless, the experiment temporally separated vergence from pursuit. Another example, from a different monkey, is presented in Fig. 10. For these data, the target was aligned with the left eye, stepped 10 deg away from the animal, and then smoothly moved toward the animal. Notice that for this case, the initial uncrossed disparity error is not symmetric but nevertheless, it still evoked a symmetric vergence response in both eyes with a latency of 88 ± 5 msec. The disparity induced motion of the left eye actually produced a retinal error since it displaced the optic axis of the eye with respect to the target. The error was subsequently corrected by small saccades and smooth pursuit eye movements. As was the case with the other monkey, the smooth pursuit latency with on trials with a large target step was 397 msec, much longer than the

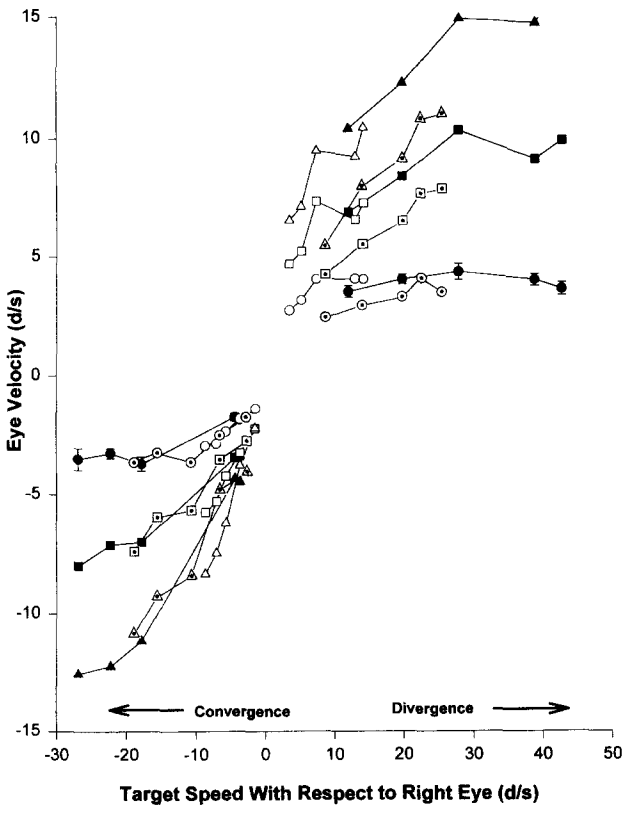

FIGURE 5. Right-eye speed as a function of target speed for three different target trajectories. Circles, squares and triangles represent early, middle, and late time periods during the open-loop interval (see Figs 3 and 4). Open symbols, symmetric mid-sagittal pursuit; solid symbols, sagittal pursuit of a target aligned with left eye; dotted open symbols, sagittal pursuit of a target eccentric to the left eye.

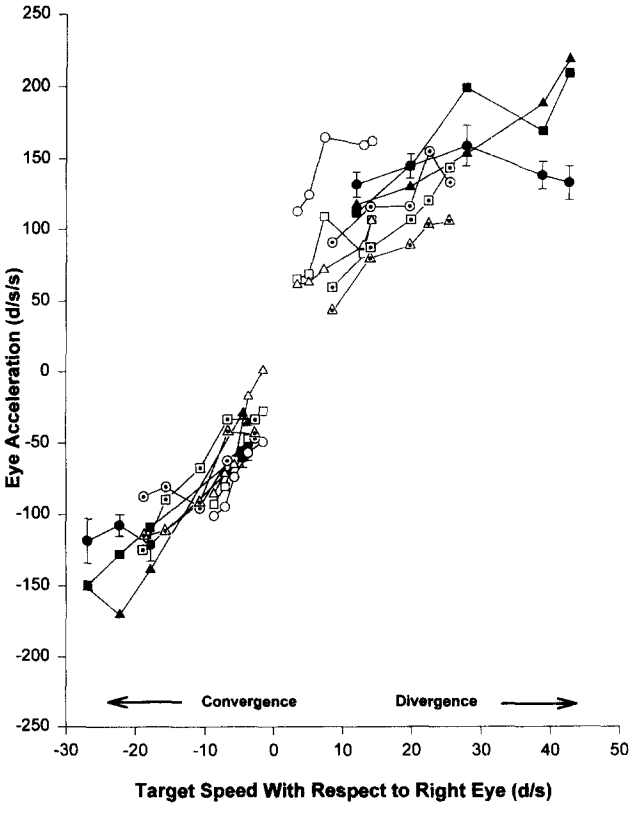

FIGURE 6. Right-eye acceleration as a function of target speed for the three target trajectories illustrated in Fig. 5. Symbols as in Fig. 5.

animal's latency (187 msec) on trials with small steps. These data clearly show that an initial target step is capable of generating a disparity driven vergence response in these experiments, but that it occurs sooner, is always symmetric, and is in the opposite direction from the later smooth pursuit response. These characteristics are evident in Figs 9 and 10 because of the large step size employed for those trials (10 deg). If the smaller steps (1–2 deg) used in most of the experiments generated similar vergence responses, they would have been much smaller than the responses shown in Figs 9 and 10 and may have escaped detection.

These data show clearly that any vergence response to the initial target step would have been directed oppositely to the pursuit response. Thus any initial interaction between disparity-driven vergence and pursuit should have reduced the initial acceleration of the pursuing eye. However, the acceleration data (Figs 4–6 and 8) show that on the contrary, the highest accelerations were achieved during the earliest open-loop intervals. Furthermore, there was no statistically significant difference in the open-loop acceleration of disjunctive and conjugate pursuit (Fig. 8), suggesting that any contribution of a disparity-driven vergence component to pursuit acceleration in the open-loop interval was negligible within the measurement error of our data.

Additional evidence for the absence of a significant disparity-driven vergence response was obtained by eliminating disparity cues in some experiments. Figure 11 compares right-eye acceleration as a function of right-eye target speed for two conditions: binocular tracking with disparity cues present and monocular tracking with the left eye occluded. For both conditions, retinal slip on the right eye was identical, and Fig. 11 shows that eye acceleration was also identical under both conditions, despite the absence of disparity cues when the left eye was occluded. Indeed, since retinal slip was monocular when the left eye was occluded, the data suggest that monocular retinal slip is sufficient to drive smooth pursuit eye movements.*

DISCUSSION

The evidence presented in this paper suggests three conclusions: first, there is no measurable difference between disjunctive and conjugate pursuit with respect to open-loop eye acceleration; second, pursuit movements of an eye can be initiated by retinal slip across that eye; and third, eye movements produced by fusional vergence

*These data were obtained with the target aligned with the left eye. The motion of the left eye, when it was occluded, depended on the preceding trials before the eye was occluded. If the target had previously been aligned with the left eye, then the left eye remained stationary during the initial disjunctive pursuit trials. After a few dozen trials, it moved in the same direction as the right eye, but not conjugately. If the target had previously been a far target that evoked conjugate pursuit, then the left eye moved in the same direction as the right eye during the initial trials, but, again, not conjugately. Thus, in the absence of retinal slip, the motion of the occluded eye appeared to depend on the animal's prior experience.

(driven by retinal position disparity) can be separated by latency and direction from eye movements produced by smooth pursuit (driven by retinal slip). The most parsimonious interpretation of these data is that the smooth pursuit system is capable of generating separate innervations of the musculature of each eye in order to produce disjunctive pursuit of a visual target. An interaction with the fusional vergence system may occur, but it is not required.

In order to visually apprehend a target and perceive a single fused image, the two eyes must be coordinated so that both foveae are directed at the target's location in space. For distantly viewed scenes, the optic axes are parallel and eye movements are conjugate, as though both eyes were driven by a common neural command. For near targets, however, the optic axes must intersect at the target's location in space and the eye movements are disjunctive. Disjunctive eye movements cannot be generated by a common neural command. To preserve the notion of a unitary "will" for disjunctive eye movements, Hering (1868) proposed that each eye was innervated by two sources, one encoding symmetric vergence of the eyes and the other encoding conjugate rotations of the eyes. In principle, any eye position can be achieved by combining two such signals. Alternatively, an eye could be innervated by its own neural command, generated in response to retinal error or slip of the target's image on that eye. Right-and left-eye innervations are equal for conjugate eye movements but different for disjunctive eye movements. These two hypotheses represent two extremes of a possible continuum of neural control schemes. Mathematically, they are equivalent. The issue is which representation is employed by the oculomotor system.

Neurophysiological and anatomical evidence can be found to support either hypothesis. For example, conjugate and vergence premotor signals have been identified in oculomotor pathways. Internuclear neurons in the abducens nucleus (AINs) are not motoneurons. Instead, they project to the contralateral oculomotor nucleus where they excite medial rectus motoneurons (Highstein & Baker, 1978). This pathway could deliver a common innervation signal to lateral rectus motoneurons of one eye and medial rectus motoneurons of the other eye thereby producing conjugate rotations of the two eyes. Single unit studies have so far failed to find any significant differences in the discharge patterns of AINs and abducens motoneurons, especially with regard to their encoding of eye position, suggesting that their activity represents a conjugate motor command to both eyes (Fuchs, Scudder & Kaneko, 1988; Gamlin, Gnadt & Mays, 1989a; King, Zhou, Tomlinson, McConville, Page, Paige & Maxwell, 1994).

Mays (1984) first characterized several groups of cells located near the oculomotor nucleus in the mesencephalic reticular formation and near the posterior commissure. These cells encode a complex signal related to vergence angle and ocular accommodation, and were named near

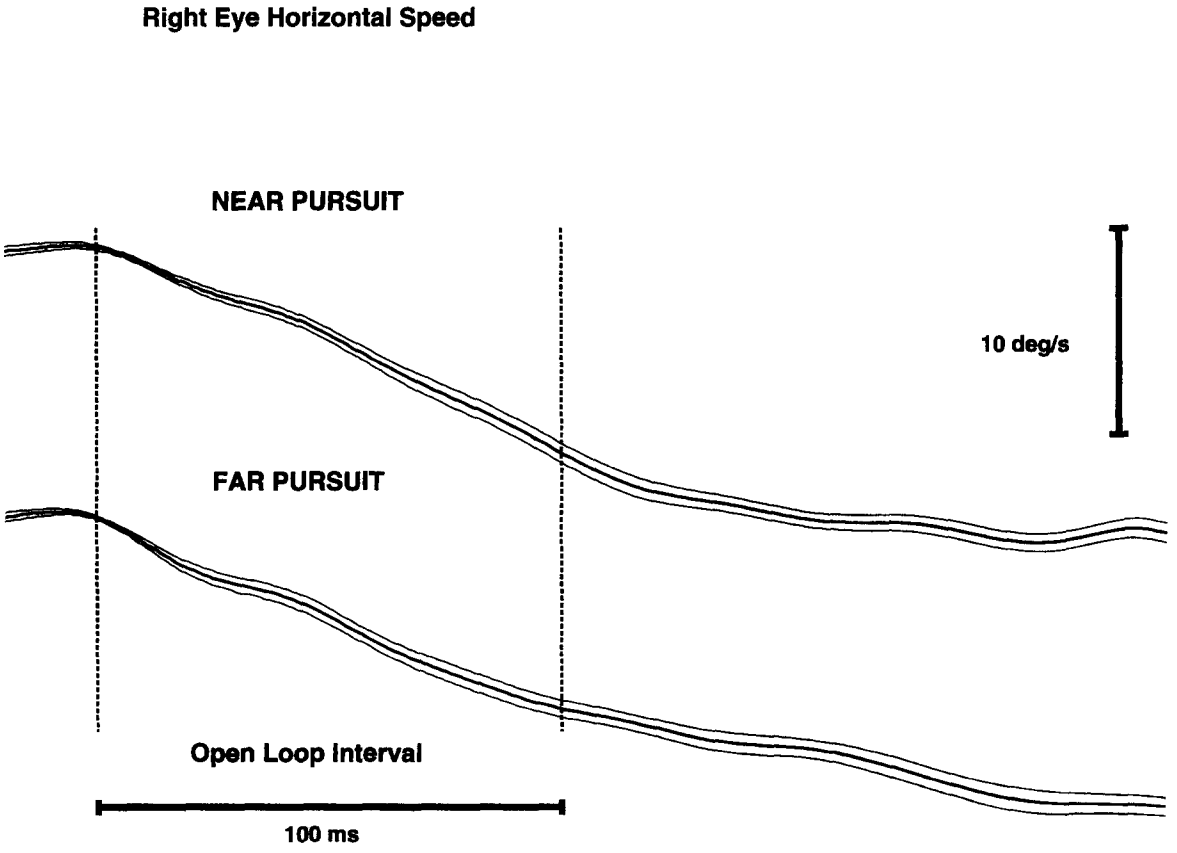

FIGURE 7. Comparison of right-eye speed during initiation of disjunctive (upper traces) and conjugate (lower traces) smooth pursuit. Averaged eye speed is shown as a bold line bracketed by a pair of thinner lines representing ± 1 SE about the mean (about 30 trials). The traces were aligned at the onset of pursuit.

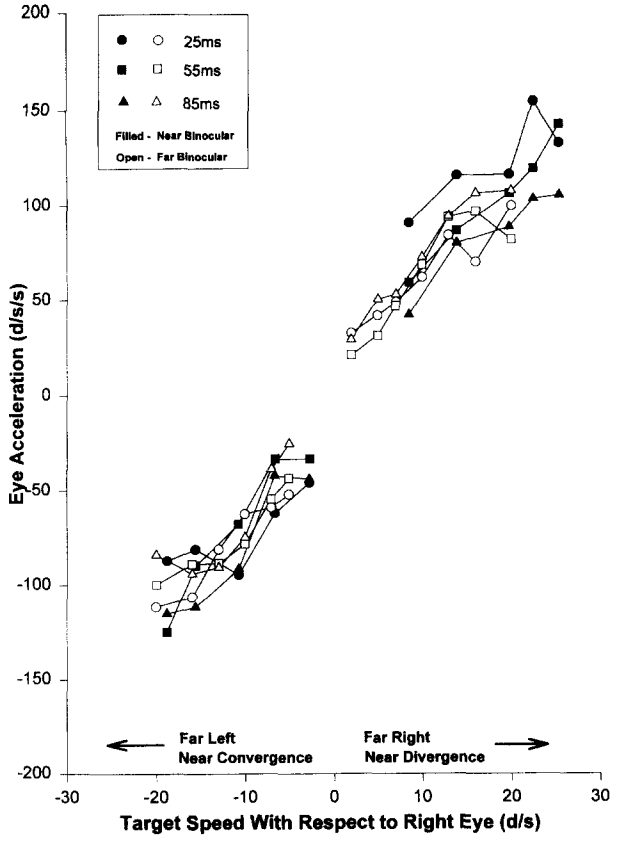

FIGURE 8. Right-eye acceleration during the open-loop interval as a function of target speed (re: the right eye) during disjunctive (solid symbols) or conjugate (open symbols) pursuit. Legend as Fig. 4.

response units (NRUs) by Judge and Cumming (1986). Many of these cells project monosynaptically to ipsilateral medial rectus motoneurons (Zhang, Gamlin & Mays, 1991). The average population response of NRUs identified as projecting to medial rectus motoneurons, was solely related to vergence angle. The accommodation responses evident in single unit discharges canceled in the population average (Zhang, Mays & Gamlin, 1992). Other studies from the same laboratory suggested that abducens neurons also received fusional vergence inputs from near response cells (Gamlin, Gnadt & Mays, 1989a,b). These studies support the idea that abducens and medial rectus motoneurons receive separate inputs encoding conjugate and fusional vergence components of eye movements, in accord with Hering's original hypothesis.

The data are not, however, conclusive. Although AINs and NRUs appear to encode conjugate and fusional vergence premotor commands respectively, they are not the only inputs to abducens and medial rectus motoneurons. Cells in the prepositus hypoglossi nucleus project to abducens and medial rectus motoneurons (McCrea, Baker & Delgado-Garcia, 1979), and the signals they convey to the two motor nuclei may not be identical. The ascending tract of Deiter's (Reisine & Highstein, 1979; Reisine, Strassman & Highstein, 1981) provides another input to medial rectus motoneurons, but the signal carried by this pathway in primates is also not well characterized. It is unlikely that quantitatively equal innervations of lateral and medial rectus motoneurons from AINs would produce equal rotations of the two eyes because of morphological differences between the muscles and fascia of the eyes. Consistent with this idea, several studies have shown that the movements of the two eyes can be differentially adapted after surgical or pharmacological modification of extraocular muscles or tendons in one eye (Viirre *et al.*, 1988). Monocular adaptation of eye movements could conceivably be accomplished by adjusting the relative conjugate and fusional vergence command strengths in both eyes, but it would be more direct to selectively modify the innervation to the perturbed eye.

Despite the general acceptance of Hering's ideas, the notion that motor commands might be organized by eye (or even muscles) is not novel. In his classic studies, Lorente de Nó (1933) showed that there were 12 VORs disynaptically linking each semicircular canal to a specific extraocular muscle in each eye. Subsequent studies have shown that the pulling directions of extraocular muscles and individual canal planes are aligned, so that physiologically and anatomically the VOR pathways are organized as canal–muscle pairs (Simpson & Graf, 1985; Henn, Suzuki, Straumann, Hess & Hepp, 1994). These studies do not imply that the direct VOR pathways are the only, or even most important, premotor pathways for vestibular related eye movements. They do, however, clearly show that single muscle or eye motor commands, rather than binocular vergence or conjugate commands, might be a pattern underlying the system's organization. Direct physiological evidence for right- or left-eye premotor signals was reported by McConville *et al.* (1994) who showed that secondary vestibular neurons in the disynaptic VOR pathways (PVP cells) encode either right- or left-eye position but not conjugate or vergence eye position. These results were obtained by having monkeys systematically view near targets so that the positions of the two eyes were disassociated. Under these conditions, the discharge of single units depended on the position of one eye but not the other eye. In a related study, King *et al.* (1994) showed that the eye position signals of abducens neurons (AINs and motoneurons) could be accounted for by summing right- and left-eye position signals such as might arise from PVP cells. They further showed that that the position signal encoded by medial rectus motoneurons could be accounted for by a similar summation of right- and left-eye signals plus an additional signal related to vergence. The vergence signal was presumed to result from NRU inputs on medial rectus motoneurons. The existence of a neural representation of vergence (as NRU discharge) is not necessarily a problem for the hypothesis that premotor commands are encoded as left- or right-eye signals. Previous studies have shown that the activity of NRUs is related to the oculomotor responses evoked by changes in the disparity or blur of a viewed scene (Judge & Cumming, 1986; Zhang *et al.*, 1992). These data suggest that the role of NRUs is to adjust and maintain ocular alignment and lens accommodation during fixation of visual targets (Zhang *et al.*, 1992). However, during saccadic gaze shifts, visual pursuit of a target moving in depth, or retinal stabilization

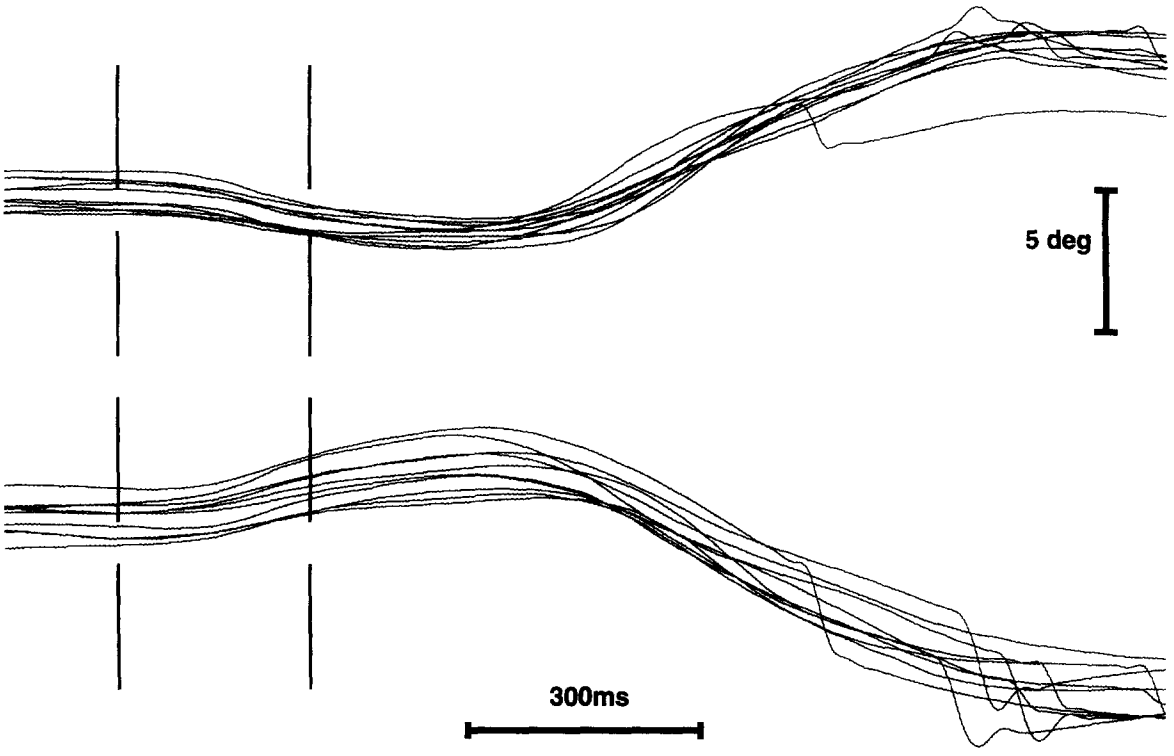

FIGURE 9. Eye position records of individual trials showing the initiation of disjunctive pursuit of a target moving in the mid-sagittal plane. The upper and lower sets of traces are horizontal position of left and right eye respectively. The initial target step was 10 deg in the divergent direction, and induced a symmetric vergence with a shorter latency than the smooth pursuit response (see text for details). The onset of the divergence movement (first vertical line) was estimated from the averaged eye velocity records (not shown) for these trials. The onset of the smooth pursuit movement was estimated from the vertical eye velocity records (not shown) (see text for details). For this reason, the onset times determined from eye speed records appear to precede changes in eye position records as shown here.

of a near target during head motion, the saccadic, smooth pursuit or vestibular systems may be able to directly generate right- and left-eye movement commands. Fusional vergence could operate in parallel with these systems to continuously adjust (over a limited range) ocular vergence so as to minimize disparity. The smooth pursuit data reported above are entirely consistent with this idea. During step-ramp target motions in depth,

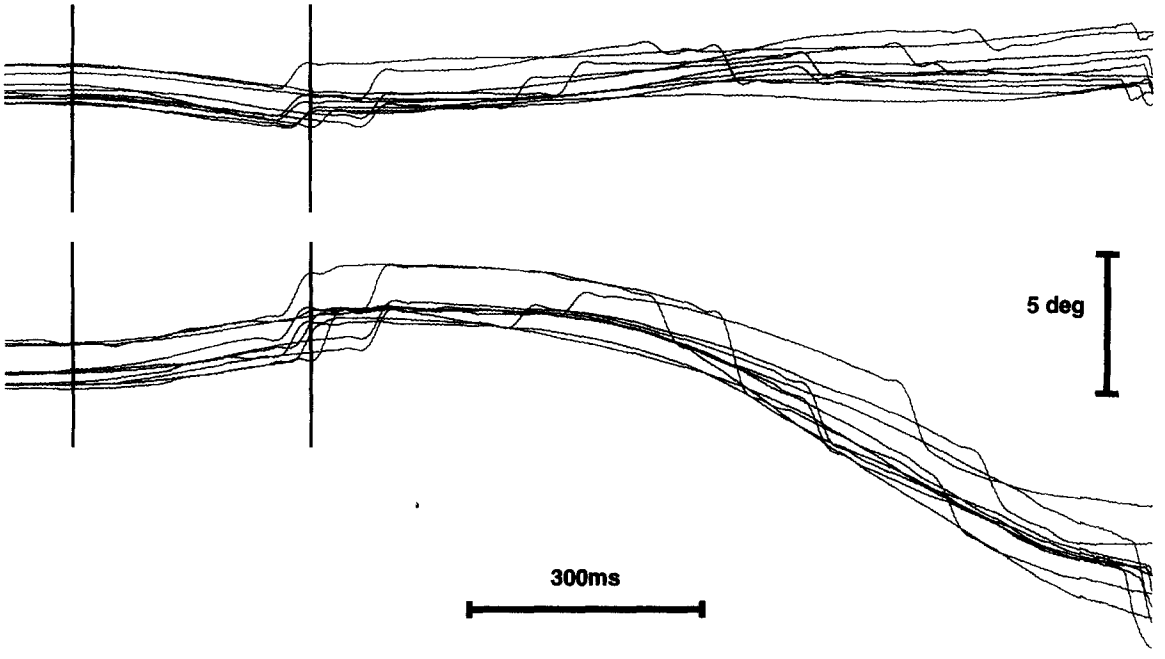

FIGURE 10. Similar to Fig. 9 except that the target was aligned with the left eye. Notice that the initial response to the target step was a symmetric vergence movement (first vertical line) that moved the left eye off of the target.

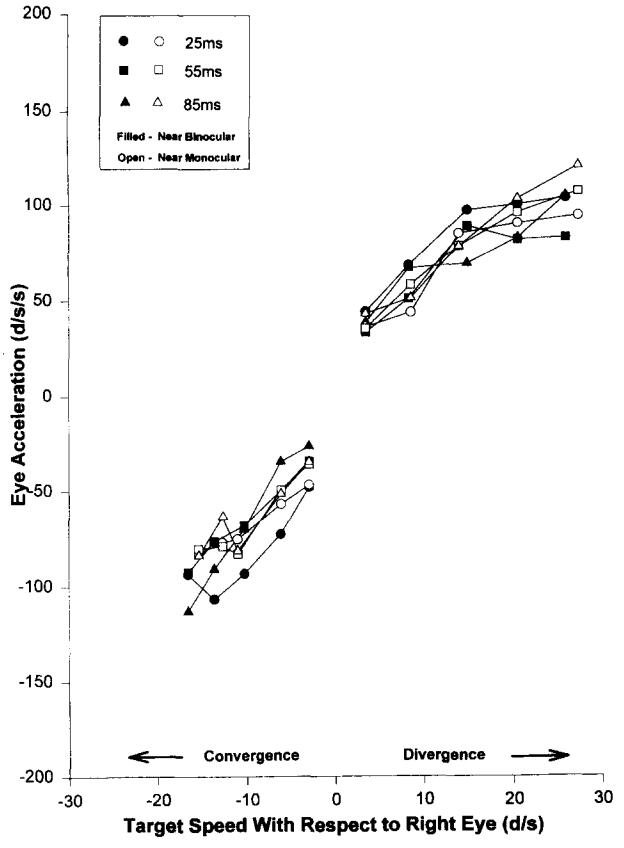

FIGURE 11. Right-eye acceleration during the open-loop interval as a function of target speed (re: right eye) with left eye occluded (open symbols) and with binocular viewing (solid symbols).

fusional vergence responses were symmetric and were evoked with a different time–course, direction, and latency from the smooth pursuit responses. Ocular acceleration, during the open-loop initiation of pursuit, was consistently related to monocular retinal slip across each eye, rather than to the conjugate and vergence components of the target's motion. Taken together, these data suggest that oculomotor commands are organized in a coordinate space defined by right and left eye movements (or muscle contractions) rather than a coordinate space defined by conjugate and vergence components.

REFERENCES

Bahill, A. T. & McDonald, J. D. (1983). Frequency limitations and optimal step size for the two point central difference derivative algorithm with applications to human eye movement data. *IEEE Transactions on Biomedical Engineering, BME-30*, 191–194.

Dodge, R. (1903). Five types of eye movements in the horizontal meridian plane of the field of regard. *American Journal of Physiology, 8*, 307–329.

Enright, J. T. (1984). Changes in vergence mediated by saccades. *Journal of Physiology, London, 350*, 9–31.

Erkelens, C. J., Collewijn, H. & Steinman, R. M. (1989). Ocular vergence under natural conditions. II. Gaze shifts between real targets differing in distance and direction. *Proceedings of the Royal Society of London B, 236*, 441–465.

Fuchs, A. F., Scudder, C. A. & Kaneko, C. R. S. (1988). Discharge patterns and recruitment order of identified motoneurons and internuclear neurons in the monkey abducens nucleus. *Journal of Neurophysiology, 60*, 1874–1895.

Gamlin, P. D. R., Gnadt, J. W. & Mays, L. E. (1989a). Abducens internuclear neurons carry an inappropriate signal for ocular convergence. *Journal of Neurophysiology, 62*, 70–81.

Gamlin, P. D. R., Gnadt, J. W. & Mays, L. E. (1989b). Lidocaine-induced unilateral internuclear ophthalmoplegia: Effects on convergence and conjugate eye movements. *Journal of Neurophysiology, 62*, 82–95.

Henn, V., Suzuki, Y., Straumann, D., Hess, B. J. M. & Hepp, K. (1994). Motoneurons of extraocular muscles code directions in vestibular coordinates. *Society of Neuroscience Abstracts, 20*, Part 2, 1399.

Hering, E. (1868). *The theory of binocular vision*. New York: Plenum Press.

Highstein, S. M. & Baker, R. (1978). Excitatory termination of abducens internuclear neurons on medial rectus motoneurons. *Journal of Neurophysiology, 41*, 1647–1661.

Judge, S. J. & Cumming, B. G. (1986). Neurons in the monkey midbrain with activity related to vergence eye movement and accommodation. *Journal of Neurophysiology, 55*, 915–930.

Judge, S. J., Richmond, B. J. & Chu, F. C. (1980). Implantation of magnetic search coils for measurements of eye position: An improved method. *Vision Research, 20*, 535–538.

Kenyon, R. V., Ciuffreda, K. J. & Stark, L. (1980). Unequal saccades during vergence. *American Journal of Optometry and Physiological Optics, 57*, 586–594.

King, W. M., Zhou, W., Tomlinson, R. D., McConville, K. M. V., Page, W. K., Paige, G. D. & Maxwell, J. S. (1994). Eye position signals in the abducens and oculomotor nuclei of monkeys during ocular convergence. *Journal of Vestibular Research, 4*, 401–408.

Leigh, R. J. & Zee, D. S. (1991). *The neurology of eye movements*. Philadelphia, Pa: F.A. Davis.

Lisberger, S. G. & Westbrook, L. E. (1985). Properties of visual inputs that initiate horizontal smooth pursuit eye movements in monkeys. *Journal of Neuroscience, 5*, 1662–1673.

Lorente de Nó, R. (1933). Vestibulo-ocular reflex arc. *Archives of Neurology and Psychiatry, 30*, 245–291.

Maxwell, J. S. & King, W. M. (1992). Dynamics and efficacy of saccade-facilitated vergence eye movements in monkeys. *Journal of Neurophysiology, 68*, 1248–1259.

Mays, L. E. (1984). Neural control of vergence eye movements: Convergence and divergence neurons in midbrain. *Journal of Neurophysiology, 51*, 1091–1108.

Mays, L. E. & Gamlin, P. D. R. (1992). Role of omnipause neurons in saccade–vergence interactions. *Society for Neuroscience Abstracts, 18*, Part 1, 27.

McConville, K. M. V., Tomlinson, R. D., King, W. M., Paige, G. D. & Na, E. Q. (1994). Eye position signals in the vestibular nuclei: Consequences for models of integrator function. *Journal of Vestibular Research, 4*, 391–400.

McCrea, R. A., Baker, R. & Delgado-Garcia, J. (1979). Afferent and efferent organization of the prepositus hypoglossi nucleus. *Progress in Brain Research, 50*, 653–665.

Ono, H. & Nakamizo, S. (1978). Changing fixation in the transverse plane at eye level and Hering's law of equal innervation. *Vision Research, 18*, 511–519.

Paige, G. D. & Tomko, D. L. (1991). Eye movement responses to linear head motion in the squirrel monkey. II. Visual–vestibular interactions and kinematic considerations. *Journal of Neurophysiology, 65*, 1183–1196.

Rashbass, C. (1961). The relationship between saccadic and smooth tracking eye movements. *Journal of Physiology, London, 159*, 326–338.

Rashbass, C. & Westheimer, G. (1961a). Independence of conjugate and disjunctive eye movements. *Journal of Physiology, London, 159*, 361–364.

Rashbass, C. & Westheimer, G. (1961b). Disjunctive eye movements. *Journal of Physiology, London, 159*, 339–360.

Reisine, H. & Highstein, S. M. (1979). The ascending tract of Deiters conveys a head velocity signal to medial rectus motoneurons. *Brain Research, 170*, 172–176.

Reisine, H., Strassman, A. & Highstein, S. M. (1981). Eye position and head velocity signals are conveyed to medial rectus motoneurons in the alert cat by the ascending tract of Deiters. *Brain Research, 211*, 153–157.

Robinson, D. A. (1963). A method of measuring eye movement using a scleral search coil in a magnetic field. *IEEE Transactions on Biomedical Engineering*, *BME-10*, 137–145.

Simpson, J. I. & Graf, W. (1985). The selection of reference frames by nature and its investigators. In Berthoz, A. & Jones, G. M. (Eds), *Adaptive mechanisms in gaze control: Facts and theories, reviews in oculomotor research* (Vol. 1, pp. 3–16). New York: Elsevier.

Snyder, L. H. & King, W. M. (1992). The effect of viewing distance and the location of the axis of rotation on the monkey's vestibulo-ocular reflex (VOR). I. Eye movement responses. *Journal of Neurophysiology*, *67*, 861–874.

Viirre, E., Cadera, W. & Vilis, T. (1988). Monocular adaptation of the saccadic system and vestibulo-ocular reflex. *Investigative Ophthalmology & Visual Science*, *29*, 1339–1346.

Yarbus, A. L. (1967). *Eye movements and vision*. New York: Plenum Press.

Zee, D. S., Fitzgibbon, E. J. & Optican, L. M. (1992). Saccade–vergence interactions in humans. *Journal of Neurophysiology*, *68*, 1624–1641.

Zhang, Y., Gamlin, P. D. R. & Mays, L. E. (1991). Antidromic identification of midbrain near response cells projecting to the oculomotor nucleus. *Experimental Brain Research*, *84*, 525–528.

Zhang, Y., Mays, L. E. & Gamlin, P. D. R. (1992). Characteristics of near response cells projecting to the oculomotor nucleus. *Journal of Neurophysiology*, *67*, 944–960.

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